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Effectiveness of low-grade weirs for nutrient removal in an agricultural landscape in the Lower Mississippi Alluvial Valley

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ABSTRACT

New best management practices (BMPs) are needed to provide enhanced water quality improvements to downstream aquatic systems from agricultural landscapes. In Mississippi, a simple process of controlled surface drainage is being advocated in drainage ditches within agricultural landscapes. Low-grade weirs (hereafter called "weirs") are low, check-dam structures where water is held in drainage ditches at multiple locations. This spatial arrangement of controlled drainage results in increases in hydraulic residence time, decreases in flow velocities at multiple locations, and potential decreases in nutrient concentrations and sediment loads. This study was the first field-scale evaluation of weirs toward storm event nutrient (nitrate – NO_3^-, nitrite – NO_2^-, ammonia – NH_3, dissolved inorganic P and total inorganic P) removal within a single ditch, Terrace, over an 18-month period. Individual sites within Terrace were monitored on rising and falling limbs of the storm hydrograph for changes in nutrient concentrations. A Hydrologic Engineering Centers River Analysis System (HEC-RAS) model was setup to calculate load derivations and differences. Overall there were very few statistical differences ($P > 0.05$) between inflow and outflow concentrations due to their nascent variability in concentration between seasons, hydrology and runoff volume. However, median mass kg/ha as well as percentage nutrient (NH_3, NO_2^-, dissolved inorganic P, and total inorganic P) load reductions were positive ranging from 14% (dissolved inorganic P) to 67% (NH_3 and NO_2^-), with the exception of a median percent increase in NO_3^- load from inflow to outflow, likely resulting from the influence of two outlying storm events. Results indicate that at the field scale, weirs within a ubiquitous landscape feature such as an agricultural drainage ditch can reduce nutrient loads moving downstream. Weirs could be considered a viable BMP in agricultural landscapes aiming to control surface nutrient runoff; however, additional research of nitrogen dynamics is warranted to ensure their efficacy.

1. Introduction

The global population increases by nearly three individuals each second, translating into an additional 79.4 million individuals annually who will need food and fiber to survive (Moore et al., 2010). To meet this demand, agricultural food production has doubled in the last 35 years (Carvalho, 2006), leading to an almost seven-fold increase in the use of nitrogen (N) fertilizer (Tilman, 1999). Consequently, increased fertilizer use has the potential to result in higher loads of nutrients being delivered from agricultural soils to surface receiving waters (Donner, 2003). This could greatly increase the transfer of nonpoint source (NPS) pollutants to estuaries and oceans (Vitousek et al., 1997). Ultimately this can lead to a 2.5-fold increase in nutrient-driven eutrophication (Tilman et al., 2001), which is now evident in locations such as the Gulf of Mexico (Mitsch et al., 2001; Rabalais et al., 2002; Rabalais, 2011). To achieve targeted 45% reductions in total N and total P (USEPA, 2008; GOMA, 2009), scientists as well as land managers will be required to identify innovative best management practices (BMPs) that will enhance nutrient removal prior to nutrients entering downstream aquatic systems (Kröger et al., 2013). Furthermore, these novel BMPs need to be seamlessly integrated into agricultural landscapes, otherwise farmers will be hesitant to adopt and utilize the technology. These structures are relatively inexpensive; rip-rap material for weirs is $800–$900 per load; previously installed weirs require 1–2 loads of rip-rap averaging about $1500–$2000 per weir. In addition to these structures being relatively inexpensive, they are currently a BMP cost-shared through NRCS practices (410, 587, 570).

Ubiquitous features of most agricultural landscapes are agricultural drainage ditches. Adequate artificial drainage, especially in

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the southeastern United States, is required for agricultural field activities and to reduce the potential of surface water ponding during crop production (Thomas, 1995). Drainage ditches are principal links between the agricultural landscape and surface receiving waters (Moore et al., 2005, 2010). Their characteristics of hydroperiod, hydric soils and hydrophytic vegetation result in drainage ditches being simple, innovative and integrative BMPs where complex physical, biological and chemical processes foster nutrient removal. Studies have shown that landowners can greatly decrease nutrients exiting the agricultural landscape and entering adjacent aquatic ecosystems by simply enhancing wetland characteristics in drainage ditches (Cooper et al., 2002; Kröger et al., 2007; Kröger, 2008; Kröger et al., 2008b; Moore et al., 2010) and through adding controlled drainage practices within the ditch (Kröger et al., 2008a, 2011a).

Controlled drainage practices have been used in various agricultural situations to reduce velocity and volume of outflow solutes, decrease water table depths, and increase storm water mitigation and sediment retention (Wesström et al., 2001; Wright et al., 2001; Needelman et al., 2007; Kröger et al., 2011a). Low-grade weirs (hereafter referred to as "weirs") are new controlled surface drainage structures consisting of an earthen dam covered with an engineered, woven filtration fabric for stabilization, which is then covered with an additional layer of limestone rock (rip-rap). These weirs are designed to be installed at multiple locations within the drainage ditch and should theoretically retain a certain volume of water based on the slope and cross-sectional area of the given ditch (Kröger et al., 2011a). Increasing the water depth keeps more soil in a saturated state, producing anaerobic conditions that promote biogeochemical processes such as nitrification, denitrification, ammonia volatilization, and plant assimilation (Gilliam et al., 1979; Gilliam and Skaggs, 1986; Lalonde et al., 1996; Reddy and Delaune, 2008). Evaluation of weirs in an artificial experimental setting suggests that weirs increase residence times (Kröger et al., 2008a) as well as decrease nitrate-N concentrations and loads over drainage ditches that do not have any controlled drainage structures (Kröger et al., 2011b). As yet, there are no field-scale data to document nutrient removal efficiencies of weirs. Validating these results with field-scale research will further strengthen our understanding of the capabilities of low-grade weirs to reduce nutrient concentrations and loads in agricultural drainage ditches.

The primary objective of this study was to assess the ability of weirs to reduce nutrient loads at the field scale within a drainage ditch receiving runoff (natural, unregulated) from an agricultural landscape under active crop production.

2. Materials and methods

2.1. Study site

A single ditch, Terrace, was utilized as field site in this study (Fig. 1) from September 2009 to June 2011. The totally length of Terrace is approximately 550 m from inflow to outflow, weirs are placed 250 m and 550 m downstream from the inflow, the average depth is approximately 2 m, and the average width is approximately 18 m. Terrace ditch drains surface runoff into the Wolf Lake, which is part of the Upper Yazoo River Watershed (HUC: 08030206), within the Lower Mississippi Alluvial Valley (LMAV), commonly referred to as the "Mississippi Delta." Terrace ditch is located approximately 14 km northwest of Yazoo City (32°57′02.63″ N, 92°25′22.80″ W) in Yazoo County, MS, receiving run-off from row-crop agriculture and abandoned catfish ponds bordering its channel. The site is dominated by silt loam soils (Dundee Silt Loam 74%/Sharkey Clay 12%) and drains approximately 960 ha of row-crop (continuous corn 2010 and 2011). Several other sites were included in the original monitoring study but Terrace was the only system where complete inflow/outflow data were captured, with a significant number of storm events occurring over the monitoring time (18 months). Water quality data was captured during the period of January 2010 through June 2011.

Terrace ditch was land formed during the summer of 2009 to include in-stream benches and two weirs. A topographic map of Terrace ditch (Fig. 2), created during October 2010, displays the elevation gradient with the profile immediately above and below the weirs. Weirs were comprised of earthen banks covered with a woven filtration fabric for stabilization and armored by a layer of limestone rock (80# rip-rap). Weir height impacted approximately 1300 m^2, or 33%, of the channel bed. Prior to 2009, the original ditch was comprised of a narrow channel overgrown with upland vegetation.

2.2. Water quality sampling

Surface flow samples from the rising and falling limbs of rain events were collected at the inflow and outflow of Terrace ditch to assess the ability of weirs to reduce nutrient concentrations and loads. Rising limb storm samples were collected on a per rain event basis from using three permanently staked passive samplers that were situated 200–1200 mm above sediment surface. Permanent staked samplers were located at the inflow and immediately downstream of each weir. An automated sampler (ISCO 6712, Teledyne, Thousand Oaks, CA) was programmed to collect outflow samples based on changes in water level below the final weir. These water levels corresponded to permanent stake sampler locations at the outflow and further upstream. Grab sampling methods were followed to collect surface flows during the falling limb using cubitainers (VWR, QC registered). Falling limb sampling was conducted on a three-week schedule during the growing season (March–October) and a six-week schedule during the dormant season (November–February). Grab samples were taken starting at the outflow and moving up the ditch system to the inflow. A total of three grab samples were taken within the ditch (outflow, below weir 1 and inflow). Water samples were also collected from any draining abandoned aquaculture pond drain pipes during falling limb sampling. Sampling of the falling limb only occurred if water was continuous and flowing within the drainage ditch. This flow was the result of antecedent rainfall conditions, as these sites do not experience regular baseflow contributions from groundwater. If water was not flowing or continuously connected through the drainage ditch no sample was taken.

Once collected, water samples were immediately placed on ice and transported to the Mississippi State University Water Quality Laboratory for nutrient analysis within 24 h. Samples were stored at 4 °C until analysis was completed. Unfiltered water samples were analyzed for total inorganic phosphorous (TIP) using sulfuric acid digestion and ascorbic acid, molybdenum blue reaction (Murphy and Riley, 1962). Filtered samples (0.45 μm) were analyzed on a HACH DR 5000 spectrophotometer (HACH, Loveland, CO) for dissolved inorganic phosphorous (DIP) (Murphy and Riley, 1962) and ammonia (NH_3; phenolate method). Nitrite and NO_x^- (NO_2^- + NO_3^-) concentrations were determined using cadmium reduction methods on a Lachat Flow Injection Analysis (FIA) 8500 (HACH®, Lachat Instruments, Loveland, CO). Nitrate values presented in the results were calculated as the difference of $[NO_x^-] - [NO_2^-]$.

2.3. Nutrient load calculation

Water level within the Terrace ditch was monitored with HOBO™ (Onset, Pocasset, MA) water level recorders. HOBO™ recorders were suspended just above the sediment on a permanent